NASA/TP-1999-209697

Concept Development of a Mach 1.6 High-Speed Civil Transport

Elwood W. Shields
Lockheed Engineering & Sciences Company, Hampton, Virginia

James W. Fenbert
Langley Research Center, Hampton, Virginia

Lori P. Ozoroski and Karl A. Geiselhart
Lockheed Engineering & Sciences Company, Hamton, Virginia

December 1999

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- Email your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Telephone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA/TP-1999-209697

Concept Development of a Mach 1.6 High-Speed Civil Transport

Elwood W. Shields
Lockheed Engineering & Sciences Company, Hampton, Virginia

James W. Fenbert
Langley Research Center, Hampton, Virginia

Lori P. Ozoroski and Karl A. Geiselhart
Lockheed Engineering & Sciences Company, Hamton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

December 1999

Available from:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

Abstract

A high-speed civil transport configuration with a Mach number of 1.6 was developed as part of the NASA High-Speed Research Program to serve as a baseline for assessing advanced technologies required for an aircraft with a service entry date of 2005. This configuration offered more favorable solutions to environmental concerns than configurations with higher Mach numbers. The Mach 1.6 configuration was designed for a 6500 n.mi. mission with a 250-passenger payload. The baseline configuration has a wing area of 8732 ft^2, a takeoff gross weight of 591570 lb, and four 41000-lb advanced turbine bypass engines defined by NASA. These engines have axisymmetric mixer-ejector nozzles that are assumed to yield 20 dB of noise suppression during takeoff, which is assumed to satisfy the FAR Stage III noise requirements. Any substantial reduction in this assumed level of suppression would require oversizing the engines to meet community noise regulations and would severly impact the gross weight of the aircraft at takeoff. These engines yield a ratio of takeoff thrust to weight of 0.277 and a takeoff wing loading of 67.8 lb/ft^2 that results in a rotation speed of 169 knots. The approach velocity of the sized configuration at the end of the mission is 131 knots. The baseline configuration was resized with an engine having a projected life of 9000 hr for hot rotating parts and 18000 hr for the rest of the engine, as required for commercial use on an aircraft with a service entry date of 2005. Results show an increase in vehicle takeoff gross weight of approximately 58700 lb. This report presents the details of the configuration development, mass properties, aerodynamic design, propulsion system and integration, mission performance, and sizing.

Introduction

In support of the NASA High-Speed Research (HSR) Program, high-speed civil transport (HSCT) baseline configurations are being developed with Mach numbers of 1.6 to 2.4. The Mach 1.6 configuration presented herein is being studied primarily as a possible solution to environmental concerns. The lower Mach number would allow the configuration to cruise at lower altitudes where the effects of engine emissions on the ozone layer are projected to be smaller. Methods for alleviation of the sonic boom may also be more readily solved at this Mach number. The Mach 1.6 configuration should also require the least time for development and testing, which would make the service entry date earlier than the higher Mach number configurations. Mach 2.4 is presently considered the upper limit for the cruise Mach number of the HSCT. This limit results from the long lead times required for developing and testing of high-temperature materials not only for the airframe structure but also for the engine materials that were necessary to ensure long-term reliability.

To develop a family of HSCT configurations, certain guidelines were established at the beginning of the design process. Unlike the highly blended wing-body configurations studied earlier in the HSR Program (ref. 1), these designs were developed with relatively simple wing planforms and without extensive wing-body blending so that parametric studies that require sizing the vehicle can be more readily accomplished. Engine nacelles were to be axisymmetric, single engine, underwing pods. The approach was to design a tailless configuration for low weight and high aerodynamic efficiency at cruise speeds. The technology level selected was intended to reflect a service entry date of 2005. This level of technology was represented in the assumptions of advanced flight controls, engine performance characteristics, and reduced aircraft structural and systems weights.

The design mission was for a distance of 6500 n.mi. with an all-supersonic cruise and a passenger load of approximately 250. The vehicle was required to be able to operate out of today's major airports. This requirement resulted in a maximum takeoff and landing field length of 11000 ft and a maximum final approach speed of 160 knots while maintaining standard fuel reserves. Although Federal Aviation Regulations presently require that flaps be at fixed deflections during takeoff and landing, by the year 2005, this requirement will be technologically obsolete. Thus, leading- and trailing-edge devices were allowed to vary for optimum performance. The configuration was optimized for the minimum takeoff gross weight required to meet the design mission.

Symbols

C_D	drag coefficient, D/qS
C_L	lift coefficient, L/qS
$\bar{c}$	mean aerodynamic chord, ft
D	drag, lb
GW	gross weight, lb
h	altitude, ft
l	length, ft
L	lift, lb
M	Mach number
q	dynamic pressure, lb/ft^2
S	reference area, ft^2
SFC	specific fuel consumption, $\frac{\text{lb/hr}}{\text{hr}}$
TOFL	takeoff field length, ft
TOGW	takeoff gross weight, lb
T/W	thrust-to-weight ratio
V	velocity, knots
W	weight, lb
x	longitudinal coordinate
x_{cg}	center of gravity, in.
y	spanwise coordinate

Subscripts:

app	approach
f	friction
I	inboard
i	induced
LEI	leading-edge inboard
LEO	leading-edge outboard
O	outboard
o	zero lift
r	roughness
ref	reference
TEI	trailing-edge inboard
TEO	trailing-edge outboard
w	wave

Abbreviations:

a.c.	aerodynamic center
B	body
c.g.	center of gravity
F	fin
FAR	Federal Aviation Regulations
FLOPS	Flight Optimization System
HSCT	high-speed civil transport
HSR	High-Speed Research
LE	leading edge
N	nacelles
TBE	turbine bypass engine
TDF	time, distance, and fuel
TE	trailing edge
W	wing

Configuration Development

A three-view sketch of the Mach 1.6 configuration is shown in figure 1. The wing planform was developed to attain good supersonic cruise performance while still maintaining adequate low-speed characteristics. The selected wing planform is shown in figure 2. Parametric studies conducted during the Mach 2.4 baseline configuration development (ref. 2) were used as guidelines in the development of the Mach 1.6 planform. These studies showed that a reduction in inboard leading-edge sweep leads to a significant performance penalty in the form of increased wave drag or a severe fuselage indentation to minimize wave drag. At a cruise Mach number of 1.6, this trend is more pronounced than at higher cruise Mach numbers because of the reduced Mach angle. Therefore, to minimize the wave-drag penalty, a relatively high inboard leading-edge sweep of 71.75° was selected. This leading-edge sweep also yields a low subsonic Mach number ($M = 0.5$) normal to the inboard leading edge during the cruise segment of the mission, helps maintain an adequate lifting length, and allows for a fuselage volume distribution that is adequate for the required number of passengers. The outboard panel size and leading-edge sweep were selected to minimize induced drag while maintaining adequate low-speed performance with a minimum effect on supersonic cruise performance.

Leading-edge flaps that are 15 percent chord are used on the outboard panel, and trailing-edge flaps that are 25 percent chord are used across the outboard panel on the trailing edge and then held at that constant chord length from there inboard. The low Mach number normal to the leading edge and the large leading-edge radii of the inboard panel result in an insensitivity to leading-edge camber that results in effective subsonic performance without leading-edge devices. This large radii also contributes to a lower overall wing weight and leaves more wing volume for fuel.

Figure 3 shows the interior layout of the fuselage. The configuration uses synthetic vision in the cockpit, which will be able to display both television views from more than one location on the aircraft and use radar and infrared displays for enhanced safety at night and in inclement weather. Ground-handling visibility should also be improved because of the multiple camera locations. The main cabin has 250 passenger seats in rows of four or five abreast at 34 in. pitch with a single aisle. Two main entrances are provided on each side, one forward and one aft just ahead of the galley and aft lavatories. There are six lavatories, two forward and four aft. The configuration has two galleys with one located adjacent to the front entrance and one located behind the aft entrance. Eight emergency exits are provided, four along each side between the forward and aft entrance doors. The present configuration has no windows to reduce weight and simplify interior environmental control. Exterior visibility is provided with flat panel television screens in the seatbacks. These screens can also be used for entertainment or for providing information about connecting flights and arrival times.

The engines are installed in four separate axisymmetric nacelles located on the aft underside of the wing. Their locations are constrained partly by the rear wing spars; however, locating the engines here takes advantage of favorable interference with the wing to reduce drag. Separate nacelles also reduce the effect that an engine unstart could have on other engines and is a safety factor in case of a catastrophic engine failure. Details of the propulsion system are discussed in a subsequent section.

The main landing gear, a two-post arrangement with six wheels per post, is located 166 ft from the nose and retracts into the fuselage below the passenger compartment. The nose gear is located 50 ft from the nose and retracts forward into the fuselage. The landing-gear system uses radial tires and carbon brakes for low weight.

Fuel is carried in 26 tanks in the wing and in 2 tanks in the fuselage. One fuselage tank is located in the aft portion of the fuselage behind the aft galley and is used primarily for center-of-gravity control. The other fuselage tank is located under the most forward portion of the cabin.

The planform of the vertical tail is shown in figure 1. The leading edge of the root airfoil is located 260 ft aft and 7.25 ft above the nose of the configuration. The airfoil is symmetrical with a maximum thickness-to-chord ratio of 2.5 percent at the 50-percent-chord station along the entire semispan. A detailed tail sizing was not performed for this configuration; however, a first-order analysis showed that the tail volume coefficient of 0.024 for the all-moving vertical tail would be adequate for one engine out at takeoff.

Table 1. Technology Assessment Weight Factors for Year 2005

Component	Weight factor
Wing[a]	0.70
Vertical	.80
Fuselage	.82
Nose gear	.85
Main gear	.75
Surface controls	.75
Hydraulics[b]	.03
Instruments[c]	.70
Electrical[b]	.95
Avionics[c]	.70
Furnishings	.85
Air conditioning[b]	.65
Anti-icing[b]	1.12
Auxiliary power[b]	.81

[a]Composites and aeroelastic tailoring.
[b]Fly-by-light and power-by-wire systems.
[c]Advanced cockpit technologies.

Mass Properties

The aircraft weights were calculated with an updated version of the Flight Optimization System (FLOPS) discussed in reference 2. The FLOPS uses empirical and semiempirical weight equations derived from current and proposed transport aircraft and theoretical structural wing weight studies for conventional metal and composite-wing structures. Technology factors consistent with the 2005 service entry date were obtained from various discipline experts at NASA Langley. These factors were used to modify the weights in FLOPS. (See table 1.) Many weight reductions resulted from utilization of advanced materials and construction techniques; however, the wing weight factor also used composite materials to obtain an additional improvement for the aeroelastic tailoring of the wing. The benefits of fly-by-light and power-by-wire systems were reflected in the weight factors for the controls, electrical, air conditioning, anti-icing, auxiliary power unit, and hydraulics systems. The hydraulic system operates at 5000 psi with titanium lines and fittings. Advanced cockpit technology, including multipurpose displays, was responsible for the reductions in instrument and avionics weights. Table 2 contains the resulting configuration mass and balance summary.

Figure 4 is a center-of-gravity (c.g.) diagram showing the available bounds of the c.g. travel when moving fuel to trim the aircraft. These data are derived from mass properties information available from reference 3. The

Table 2. Mass and Balance Summary

Item	W_{ref}, percent	W, lb	l_{ref}, percent	x_{cg}, in
Structure				
Wing	8.20	48501	54.5	1929.5
Vertical tail	0.20	1169	95.4	3378.8
Fuselage	7.23	42750	50.0	1769.2
Landing gear	2.47	14587	53.2	1883.2
Total	18.09	107007	53.0	1875.0
Propulsion				
Engines/nacelles	5.37	31758	69.7	2468.0
Miscellaneous systems	0.14	824	63.0	2229.3
Fuel system-tanks and plumbing	0.76	4500	61.5	2177.6
Total	6.27	37082	68.6	2427.5
Systems and equipment				
Surface controls	0.91	5393	58.6	2074.5
Auxiliary power	0.19	1149	91.5	3240.0
Instruments	0.15	891	33.3	1179.9
Hydraulics	0.65	3859	54.4	1925.1
Electrical	0.78	4635	36.1	1278.6
Avionics	0.25	1502	32.4	1148.1
Furnishings and equipment	3.56	21049	48.3	1710.7
Air conditioning	0.54	3178	54.6	1931.3
Anti-icing	0.05	325	53.3	1885.9
Total	7.10	41981	49.7	1758.0
Empty weight	31.45	186070	55.3	1958.7
Flight crew and baggage (2)	0.08	450	16.9	600.0
Cabin crew and baggage (7)	0.19	1130	50.0	1769.2
Unusable fuel	0.18	1058	53.9	1908.0
Engine oil	0.06	327	69.7	2468.0
Passenger service	0.69	4101	50.0	1769.2
Operating empty weight	32.65	193136	55.1	1951.0
Passengers (250)	6.97	41250	50.0	1769.2
Passenger baggage	1.86	11000	50.0	1769.2
Miscellaneous items	0.43	2545	50.0	1769.2
Zero fuel weight	41.91	247931	54.0	1910.8
Mission fuel and reserves	58.09	343643	53.9	1908.0
Ramp (gross) weight	100.00	591574	53.9	1909.2

takeoff gross weight is also shown along with the main landing gear location, zero-fuel weight, operating weight, and empty weight locations.

Aerodynamics Design

Zero-Lift Drag

Zero-lift drag is comprised of skin-friction drag, form drag, roughness drag, and wave drag. Skin-friction drag was calculated with the T′ method of Sommer and Short (ref. 4). Form drag was calculated with the geometry-dependent factors of the method of reference 5, and roughness drag was calculated empirically as a percentage of skin-friction drag. Zero-lift wave drag was optimized with the method of reference 6. Wave-drag optimization proved to be particularly difficult at Mach 1.6 as compared with higher Mach numbers. At Mach 1.6, the Mach angle is reduced and the resulting consequences are a reduction in the "natural smoothing" and lengthening of the overall area distribution. This effect was countered somewhat by keeping the inboard wing sweep high to spread wing volume and lift. Still, aggressive fuselage contouring was necessary to minimize wave drag. The engine nacelles also have a more pronounced effect on wave drag due to significant area growth from inlet capture to maximum diameter. The average-equivalent-body area distribution of the various configuration components is shown in figure 5. A buildup of the total zero-lift drag is shown as a function of Mach number in figure 6 at a representative cruise altitude of 50000 ft. Landing-gear drag was estimated based on unpublished data for a similar configuration that was scaled to match the frontal area of the struts and tires.

Lift-Dependent Drag

The camber and twist of the configuration were optimized for supersonic cruise with the modified linearized-theory, attached-flow method of reference 7, which accounts for the effect of leading-edge thrust and vortex lift. The supersonic drag polars, lift curves, and static longitudinal stability characteristics were then developed with the same method. Empirical design guidelines (ref. 8) that enhance the ability of this method to design camber surfaces and calculate polars that agree better with experimental results were applied to the design and analysis process. The results were then adjusted for the thrust increment caused by the downward nozzle deflection of 5° and the turning of the engine flow by the nacelle before nozzle entry. Figure 7 shows the supersonic total drag polars at Mach 1.2, 1.4, and 1.6 at a representative cruise altitude of 50000 ft.

The linearized-theory, attached-flow method of reference 9 was used to determine the subsonic polars. This method also accounts for the effects of leading-edge thrust and vortex forces. The subsonic drag polars were modified to account for the effect of a downward nozzle deflection of 5° as well as supercirculation induced on the wing by the deflected thrust (ref. 10) and internal flow turning. Figure 8 shows the subsonic total drag polars at Mach 0.6, 0.8, and 0.9 at a representative subsonic cruise altitude of 30000 ft. Transonic polars were developed with an empirical method in conjunction with the previously developed supersonic and subsonic polars.

Takeoff and landing polars were developed with the methods of references 7 and 9. An indication of the leading- and trailing-edge flap settings for best performance were developed with the method of reference 7 to determine an optimum camber surface for the required takeoff and landing lift coefficients on "restricted areas" of the wing that represent the flap locations. From these results, actual flap deflections were chosen, and a matrix of flap settings surrounding these initial deflections were analyzed with the method of reference 9 to develop a family of trimmed polars. For takeoff, schedules for both leading- and trailing-edge flaps were developed from the matrix of trimmed polars. For landing, a constant leading-edge flap deflection was chosen and a trailing-edge schedule was developed. The takeoff and landing polars are shown in figure 9, and the flap schedules are shown in figure 10.

Maximum Lift-Drag Ratio

Figure 11 shows the maximum trimmed lift-drag ratio plotted against Mach number at 30000 ft and 50000 ft, which are representative of subsonic and supersonic cruise altitudes, respectively. The maximum ratios vary from 16.4 at Mach 0.93 to 11.3 at Mach 1.6

Propulsion System and Integration

The engine is a nonafterburning turbine bypass engine (TBE) deck developed by NASA. The TBE is essentially a turbojet with a valve that allows compressor discharge air to bypass the primary burner and the turbines. As the engine power is reduced, the amount of bypass air decreases; thus, the inlet airflow remains constant and reduced spillage and boattail drag result. The overall pressure ratio, which is dictated by the maximum allowable compressor exit temperature, the maximum turbine inlet temperature, and the propulsion system weight (ref. 11) are consistent with the service entry date of 2005. The aggressive application of advanced materials and component technology utilizing ceramic and composite materials will be necessary to make this possible. Customer bleed and power extraction are 1.0 lb/sec and 200 hp, respectively. The Navy/NASA Engine Program (ref. 12) combined with an installation module based on reference 13 was used to predict installed propulsion system performance. Figures 12 and 13 show the installed propulsion system performance characteristics for various altitudes. The effect of inlet spillage and nozzle boattail drags is included in the data. The installed engine weight based on 41 000 lb of thrust at takeoff is 8146 lb each. The engine thrust-to-weight ratio (*T/W*) is 5.03. The inlet is an axisymmetric, external compression, translating centerbody inlet, and the nozzle is an axisymmetric, mixer-ejector nozzle designed to entrain external air to reduce noise during takeoff by 20 dB. This level of suppression is assumed to satisfy FAR Stage III noise requirements. However, achieving this amount of noise reduction and still maintaining a high cruise thrust coefficient will be a challenge. The engine nozzles are deflected downward 5° so that the gross thrust vector develops a lift component and minimizes moment changes with thrust level. The scaled nacelle and engine geometry is shown in figure 14.

Mission Performance and Sizing

The estimated vehicle performance and the results of sizing the wing area and thrust for minimum TOGW are

Table 3. Mission Summary

[Design range, 6500 n.mi.; flight time, 456.6 min; block time, 7.88 hr; block fuel, 309797 lb]

Segment	Initial weight, lb	Fuel, lb		Time, min		Distance, n.mi.		Mach number		Altitude, ft	
		Segment	Total	Segment	Total	Segment	Total	Start	End	Start	End
Taxi out	591574	1072	1072	10.0	10.0						
Takeoff	590502	606	1679	0.9	10.9			0.300		0	
Climb	589896	38553	40232	35.9	46.8	345.8	345.8	0.300	1.600	0	46376
Cruise	551343	264873	305105	387.1	433.9	5921.2	6267.0	1.600	1.600	46376	60004
Descent	286470	4156	309261	33.6	467.5	233.0	6500.0	1.600	0.300	60004	0
Reserves	282314	34382	343643								
Taxi in		536		5.0	472.5						
Zero fuel	247931										

presented in this section. Schematics of the design mission profile and reserve mission are shown in figure 15. A mission summary for the configuration is given in table 3. This mission includes the following:

1. Fuel for 10-min warm-up and taxi out at idle power
2. Actual fuel usage for takeoff to start of climb
3. Time, distance, and fuel (TDF) for actual climb (minimum fuel to climb path)
4. TDF for cruise at best altitude at Mach 1.6
5. TDF for actual descent at maximum *L*/*D*, idle fuel flow
6. Reserve fuel allowance (no range credit) includes the following:

   Missed approach

   Climb to reserve cruise condition

   Cruise at Mach 0.9 and best altitude 250 n.mi., including climb and descent

   Hold for 30 min at Mach 0.6 and best altitude for minimum fuel flow

   Actual descent from hold condition at maximum *L*/*D* ratio, zero thrust

   Additional fuel reserve allowance is 5 percent of trip fuel (events 3 to 5)
7. No time, fuel, or distance credit or penalty for approach, landing, or taxi in

Figure 16 is a sizing diagram developed for this configuration with FLOPS. All potential configurations represented in this design space meet requirements of the 6500 n.mi. mission. The minimum gross weight configuration meeting all mission constraints weighs 574000 lb and has a wing area of 7300 ft^2 with an engine thrust level of 38000 lb. This configuration is sized by the takeoff field length of 11000 ft and fuel volume limit. Experience has shown that approximations in the sizing equations make it difficult to reliably size the configuration over a large range to meet minimum constraints. The statistical methods used to scale fuel volume lack sufficient sensitivity to reliably scale over large changes in wing area. Although the redesigned configuration with a smaller wing area would have a lower cruise altitude, the baseline configuration with 8732 ft^2 and 41000 lb thrust is considered an acceptable vehicle with a gross weight of less than 3 percent over the theoretical minimum shown in figure 16. This baseline configuration yields a takeoff thrust to weight ratio of 0.277 and a takeoff wing loading of 67.8 lb/ft^2. The larger wing area of the baseline leaves a reasonable c.g. margin for trimming during takeoff and some flexibility as to where fuel can be placed in the configuration. The larger engine thrust level allows extra margin on takeoff field length which, in turn, may allow advanced takeoff procedures to be used for further noise reduction. As more accurate low-speed aerodynamics become available and the moment center can be more precisely defined, the sizing of the baseline can be reevaluated.

Resizing

The utility of the baseline configuration to evaluate the effects of technologies on a Mach 1.6 configuration is shown in a typical resizing exercise. The propulsion experts in the HSR Program during the design cycle of this baseline reevaluated the level of technology that would be available for a vehicle with a service entry date of 2005. It was concluded that the original engines used for this baseline would not provide the service life required for commercial use. Therefore, an alternate engine was designed to provide a projected life of

9000 hr for the hot rotating parts and 18 000 hr for the rest of the engine. This requirement results in both an increase in weight and a decrease in efficiency. The standard day performance characteristics of this alternate engine are shown in figures 17 and 18. The effect of these alternate engines on the current design can be shown by resizing the configuration with the new engines installed. The greater fuel burn and heavier weights of these engines are the main reason for the increased vehicle weight. As shown in figure 19, the wing area and engine thrust increased over the minimum takeoff gross weight configuration primarily due to the poorer performing engines. The resized configuration has a wing area of 7700 ft^2 and 41 500-lb-thrust engines. The 650672 lb TOGW is an increase of approximately 58 700 lb over that of the original configuration.

Concluding Remarks

A baseline Mach 1.6 high-speed civil transport configuration was developed as the lowest cruise Mach number of interest for a family of baselines in support of the NASA High-Speed Research Program. This lower Mach number would allow cruise at lower altitudes where the effects of engine emissions on the ozone layer are projected to be smaller and where sonic boom alleviation may be more readily solved. The availability of composite materials capable of handling the lower skin temperatures should allow for the earliest possible service entry date.

Details of the configuration development, mass properties, aerodynamic design, propulsion system integration, mission performance, and sizing were presented. The configuration is unblended with a relatively simple planform and has four engines mounted in separate axisymmetric underwing nacelles. The vehicle is designed to carry 250 passengers a distance of 6500 n.mi. with reserve fuel. The intentionally simple layout is intended to facilitate system studies investigating the effects of applying advanced technologies to the baseline concept.

The planform has been designed to minimize supersonic drag due to lift and wave drag while maintaining good low-speed characteristics. The flap arrangement includes trailing-edge flaps on both inboard and outboard portions of the wing and leading-edge flaps on the outboard portions only. This arrangement minimizes weight and complexity while providing adequate lift for takeoff and landing.

Advanced composite materials used in conjunction with innovative structural designs were used to reduce weight. Systems integration including synthetic vision for the cockpit and the use of electric actuators for the control surfaces also helped reduce weight. Weight factors that reflect these effects were developed with the help of discipline experts at NASA Langley and NASA Lewis Research Centers.

The engine used in the development of this configuration is a turbine bypass engine defined by NASA. The aggressive development and application of advanced ceramic and composite materials and their utilization in engine components is necessary to help meet weight and performance goals. An effective mixer-ejector nozzle capable of 20 dB suppression is critical to the viability of the turbine bypass engine. Any substantial reduction in the suppression level would require oversizing the engines to meet community noise regulations and would severely impact the aircraft takeoff gross weight (TOGW).

The baseline configuration has a wing area of 8732 ft^2 and a TOGW of 591 570 lb. The four advanced turbine bypass engines each have 41 000 lb thrust and weigh 8146 lb. The takeoff thrust-to-weight ratio and wing loading are 0.277 and 67.8 lb/ft^2, respectively.

A resizing of the baseline configuration with an engine that has the projected life for commercial use on a vehicle with a service entry date of 2005 was also performed. The resized configuration has a wing area of 7700 ft^2 and 41 500-lb-thrust engines. The 650672-lb TOGW is an increase of approximately 58 700 lb over that of the original configuration.

NASA Langley Research Center
Hampton, VA 23681-0001
December 2, 1994

References

1. Robins, A. Warner; Dollyhigh, Samuel M.; Beissner, Fred L., Jr.; Geiselhart, Karl; Martin, Glenn L.; Shields, E. W.; Swanson, E. E.; Coen, Peter G.; and Morris, Shelby J., Jr.: *Concept Development of a Mach 3.0 High-Speed Civil Transport.* NASA TM-4058, 1988.

2. Fenbert, James W.; Ozoroski, Lori P.; Geiselhart, Karl A.; Shields, Elwood W.; and McElroy, Marcus O.: *Concept Development of a Mach 2.4 High-Speed Civil Transport.* NASA/TP-1999-209694, 1999.

3. McCullers, L. A.: Aircraft Configuration Optimization Including Optimized Flight Profiles. *Recent Experiences in Multidisciplinary Analysis and Optimization,* Jaroslaw Sobieski, compiler, NASA CP-2327, Part 1, 1984, pp. 395–412.

4. Sommer, Simon C.; and Short, Barbara J.: *Free-Flight Measurements of Turbulent-Boundary-Layer Skin Friction in the Presence of Severe Aerodynamic Heating at Mach Numbers From 2.8 to 7.0.* NACA TN 3391, 1955.

5. USAF Stability and Control Datcom. Contracts AF33(161)-6460 and F33615-76-C-3061, McDonnell Douglas Corp., Oct. 1960. (Rev. Apr. 1978.)

6. Harris, Roy V., Jr.: *An Analysis and Correlation of Aircraft Wave Drag*. NASA TM X-947, 1964.

7. Carlson, Harry W.; and Darden, Christine M.: *Validation of a Pair of Computer Codes for Estimation and Optimization of Subsonic Aerodynamic Performance of Simple Hinged-Flap Systems for Thin Swept Wings*. NASA TP-2828, 1988.

8. Carlson, Harry W.; and Mann, Michael J.: *Survey and Analysis of Research on Supersonic Drag-Due-to-Lift Minimization With Recommendations for Wing Design*. NASA TP-3202, 1992.

9. Carlson, Harry W.; Darden, Christine M.; and Mann, Michael J.: *Validation of a Computer Code for Analysis of Subsonic Aerodynamic Performance of Wings With Leading- and Trailing-Edge Flaps With a Canard or Horizontal-Tail Surface and an Application to Optimization*. NASA TP-2961, 1990.

10. Parlett, Lysle P.; and Shivers, James P.: *Low-Speed Wind-Tunnel Tests of a Large-Scale Blended-Arrow Advanced Supersonic Transport Model Having Variable-Cycle Engines and Vectoring Exhaust Nozzles*. NASA TM X-72809, 1976.

11. Onat, E.; and Klees, G. W.: *A Method To Estimate Weight and Dimensions of Large and Small Gas Turbine Engines*. NASA CR-159481, 1979.

12. Ball, W. H.; and Hickcox, T. E.: *Rapid Evaluation of Propulsion System Effects*, Volume 1. AFFDL-TR-78-91-VOL-1, U.S. Air Force, July 1978. (Available from DTIC as AD B031 629L.)

13. Fishbach, Laurence H.; and Gordon, Sanford: *NNEPEQ: Chemical Equilibrium Version of the Navy/NASA Engine Program*. NASA TM-100851, 1988.

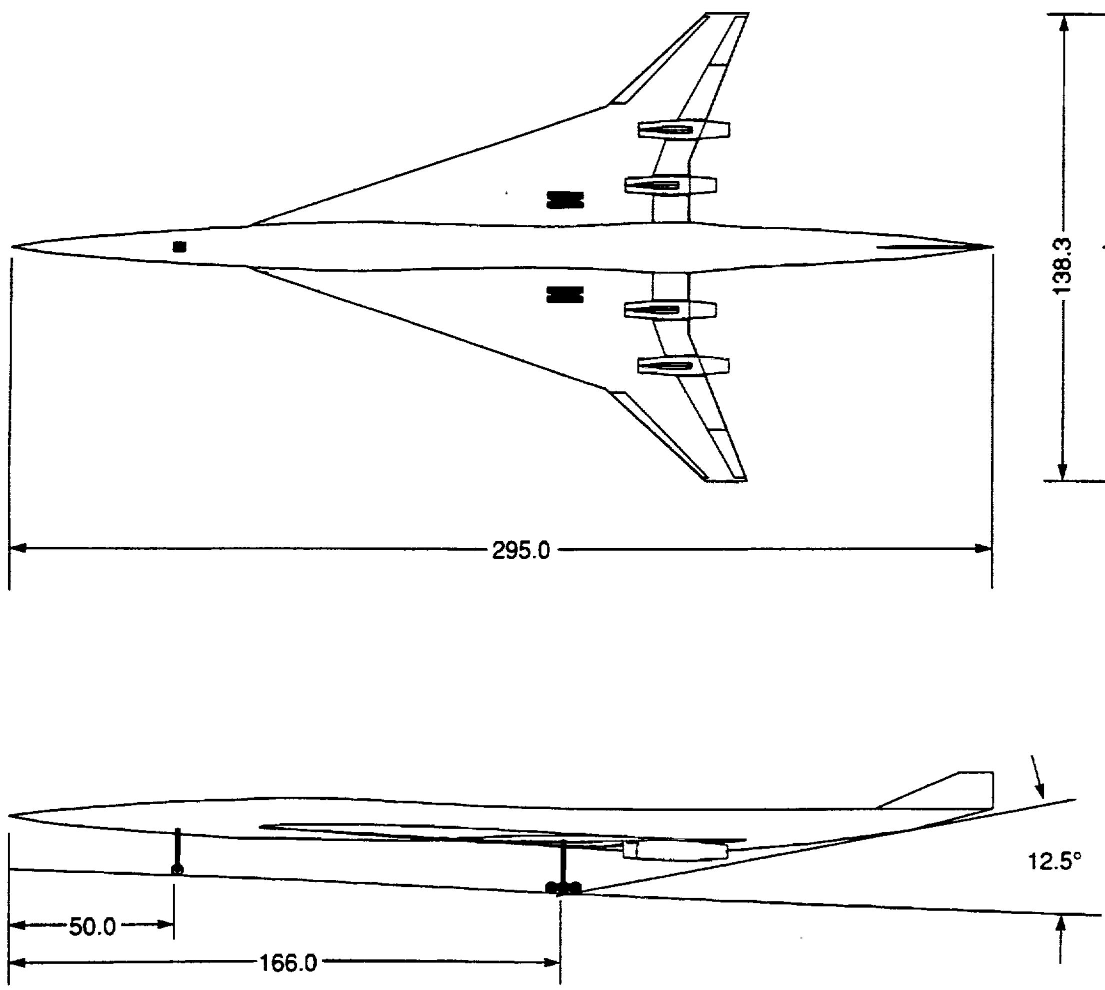
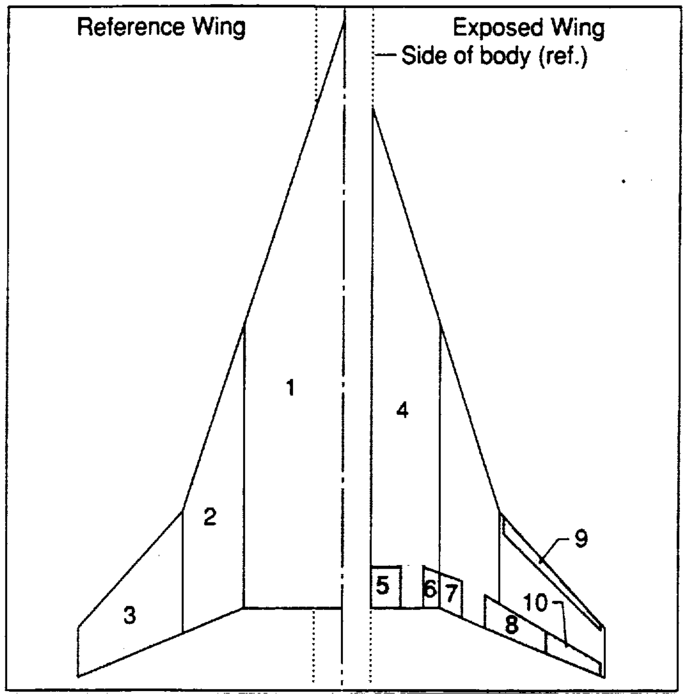


Figure 1. Three-view sketch of Mach 1.6 configuration. Linear dimensions in feet.



Component	1	2	3	Total
Wing area, ft	5832.7	1684.0	1216.12	8732.9
Aspect ratio	0.45865	0.60862	2.45235	2.19175
Taper ratio	0.483983	0.430204	0.407452	0.084836
LE sweep, deg	71.75	71.75	47.75	
TE sweep, deg	0	22.5	22.5	
Span, ft	51.722	32.014	54.612	138.35
Root chord, ft	151.98	73.56	31.64	
Tip chord, ft.	73.56	31.64	12.89	
$\bar{c}$, ft.	117.31	55.38	23.58	92.32
$\bar{c}_y$, ft	11.43	6.94	11.73	21.43
Length, ft.				169.92

Coordinate	Coordinates, ft, for component—									
	1	2	3	4	5	6	7	8	9	10
x_{LEI}	0	78.43	126.97	22.75	141.33	141.33	142.82	148.44	128.07	157.81
x_{TEI}	151.98	151.98	158.61	151.98	151.98	151.98	151.98	157.01	132.73	163.64
y_I	0	-25.86	-41.87	7.5	7.5	21.5	25.86	38.0	42.87	54.0
x_{LEO}	78.43	126.97	157.03	78.43	141.33	142.82	144.92	157.81	155.93	166.12
x_{TEO}	151.983	158.61	169.92	151.98	151.98	151.98	154.53	163.64	157.66	169.51
y_O	-25.86	-41.87	-69.17	25.86	15.5	25.86	32.0	54.0	68.17	68.17

Figure 2. Configuration planform definition.

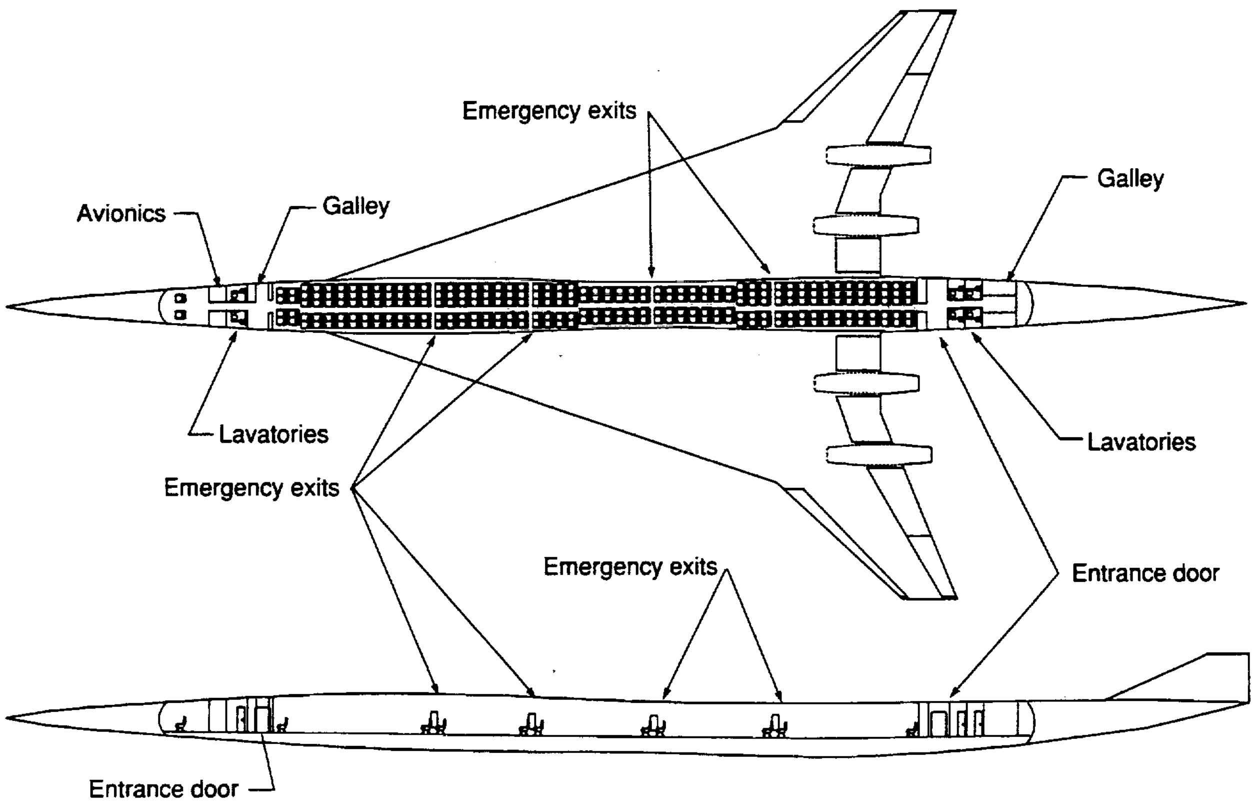


Figure 3. Interior layout of fuselage.

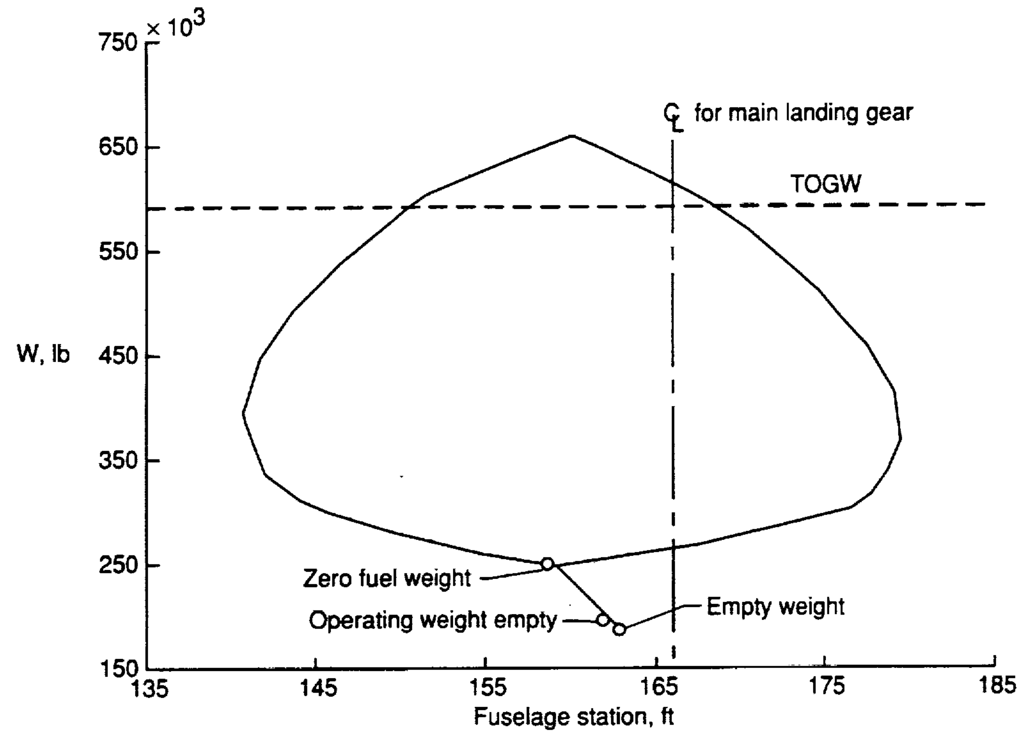


Figure 4. Center-of-gravity envelope.

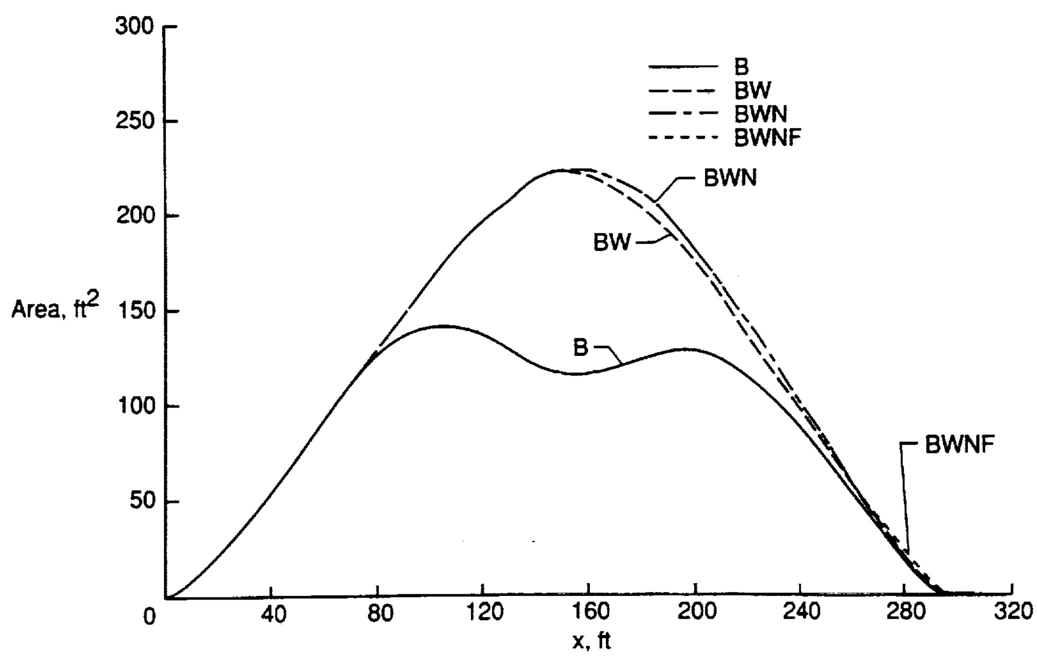


Figure 5. Area distribution of average equivalent body at Mach 1.6.

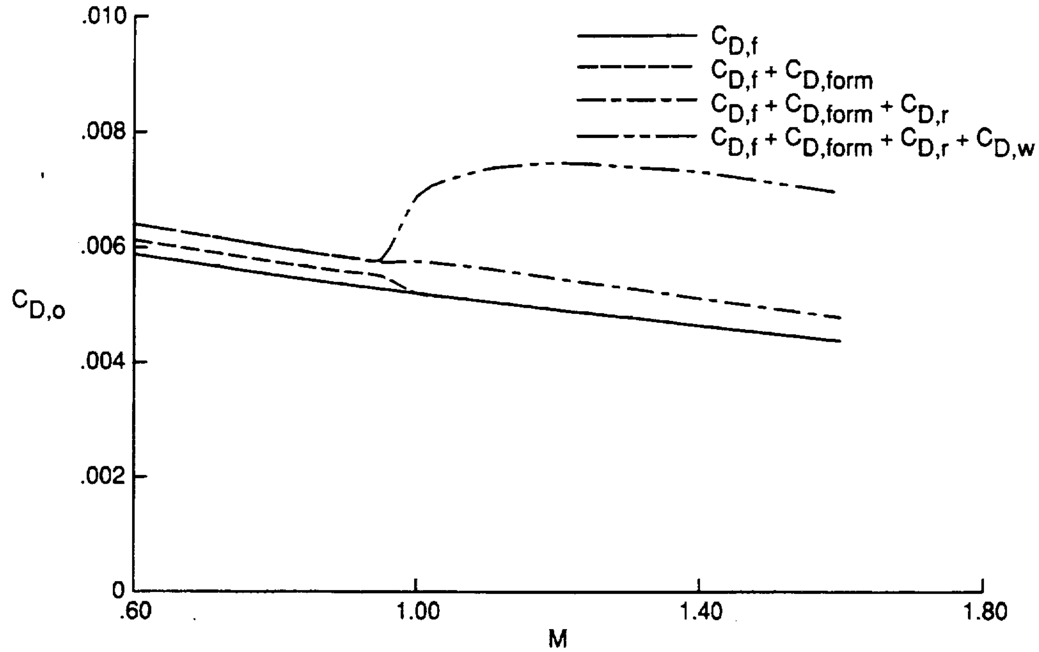


Figure 6. Zero-lift drag buildup as a function of Mach number at h = 50000 ft.

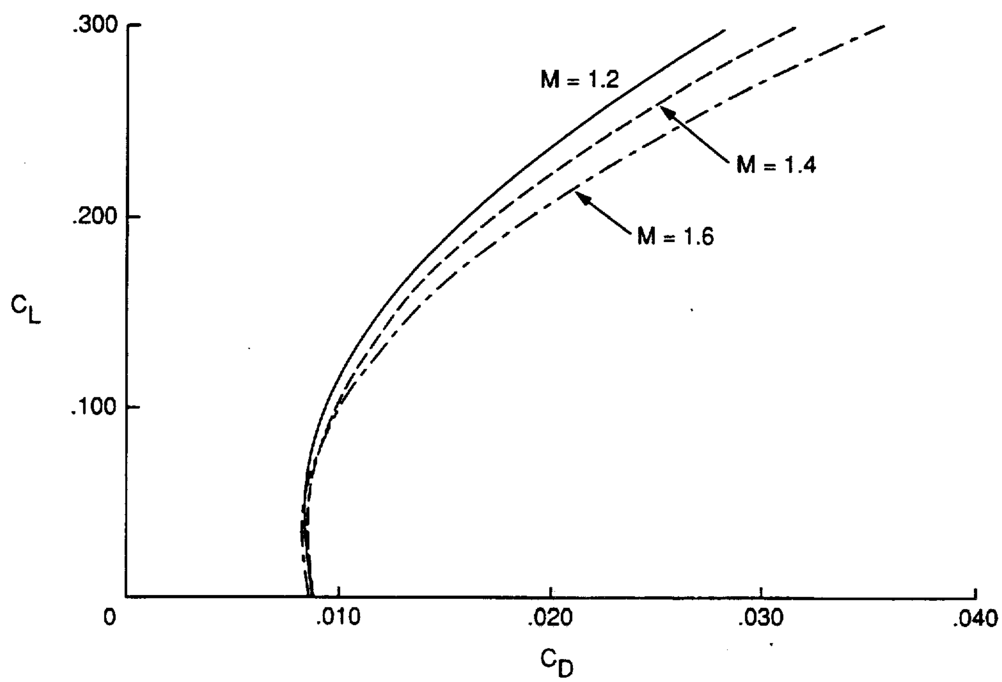


Figure 7. Supersonic total drag polars at h = 50000 ft.

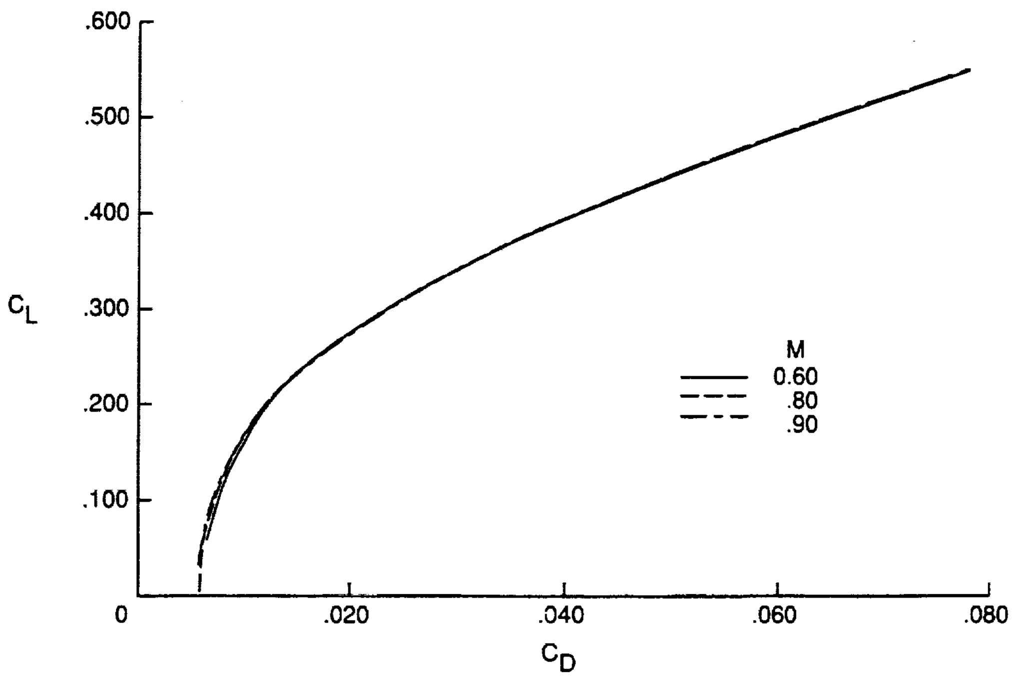


Figure 8. Subsonic total drag polars at h = 30000 ft.

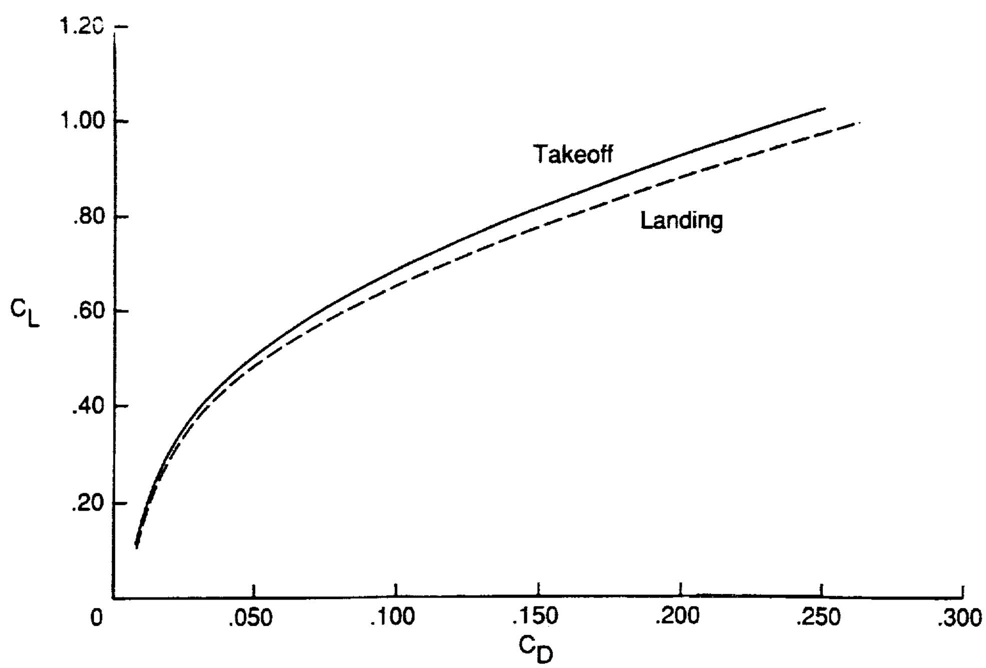
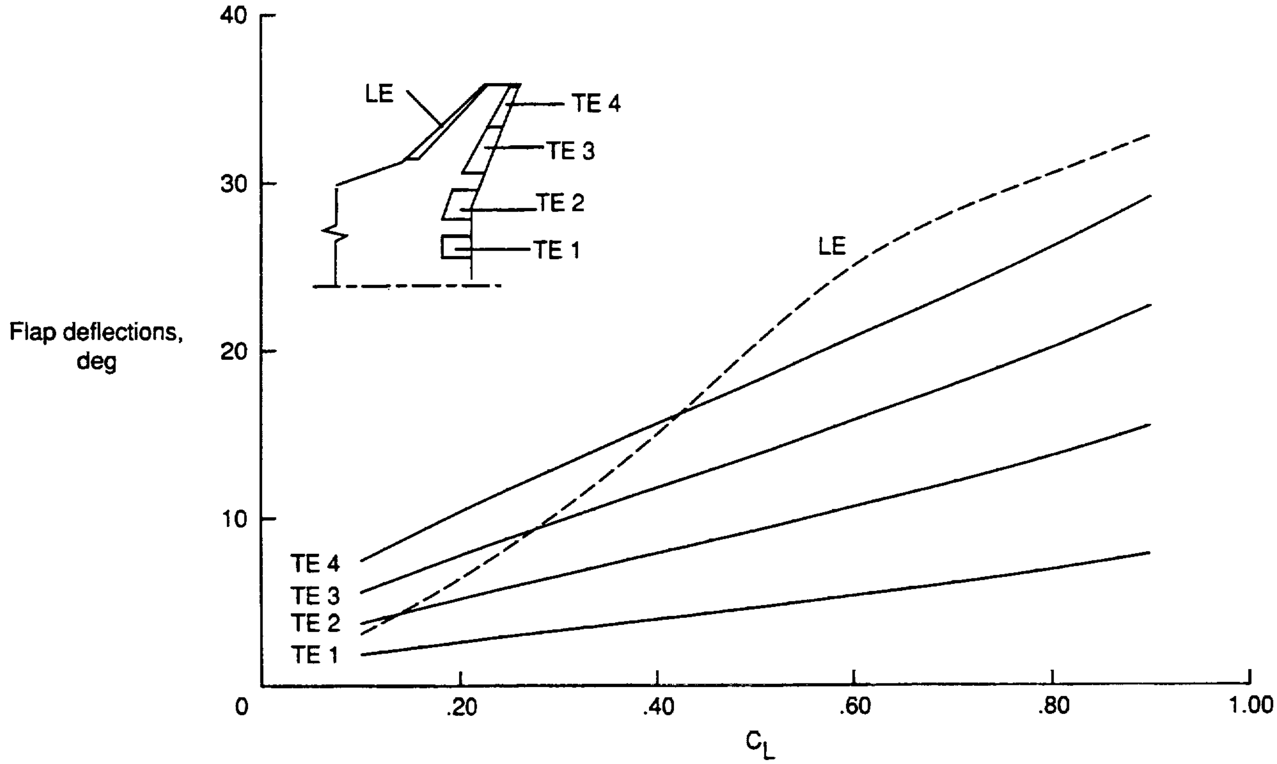
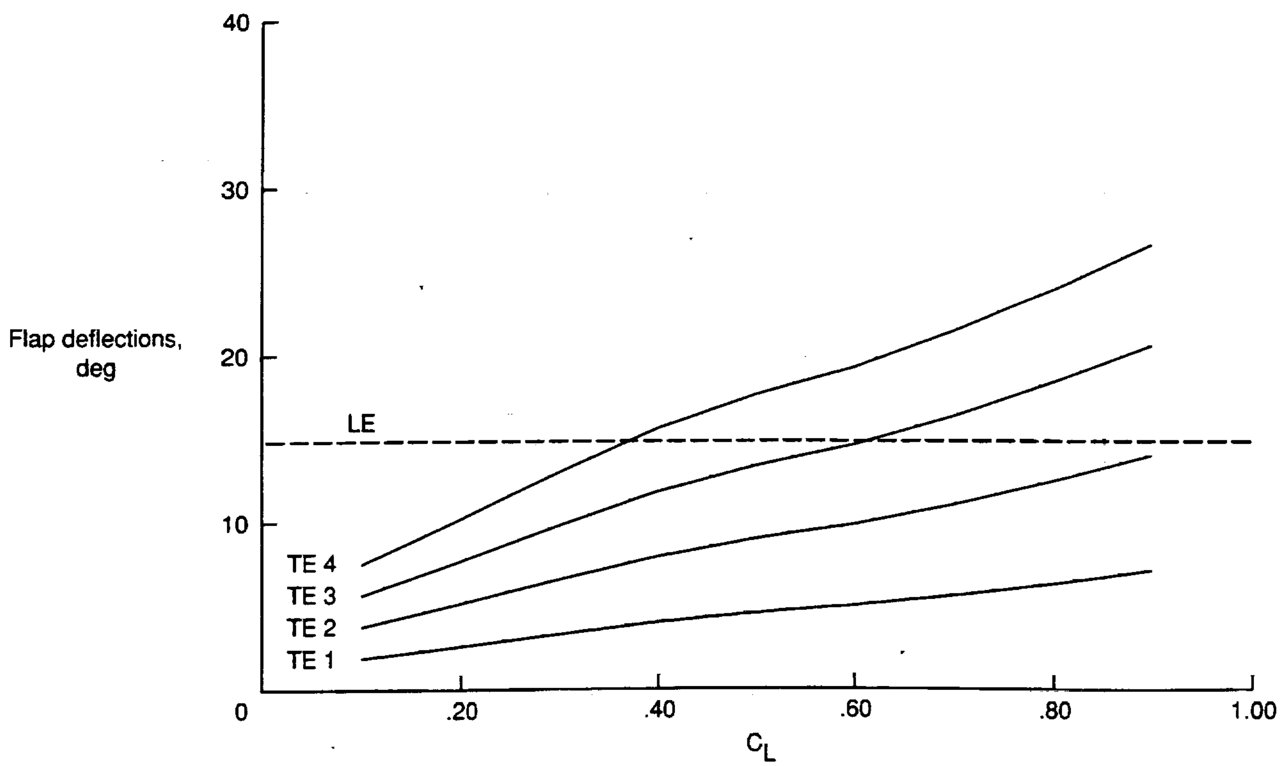


Figure 9. Trimmed takeoff and landing polars at M = 0.3 and h = 0 ft.



(a) Takeoff.



(b) Landing.

Figure 10. Programmed flap schedules.

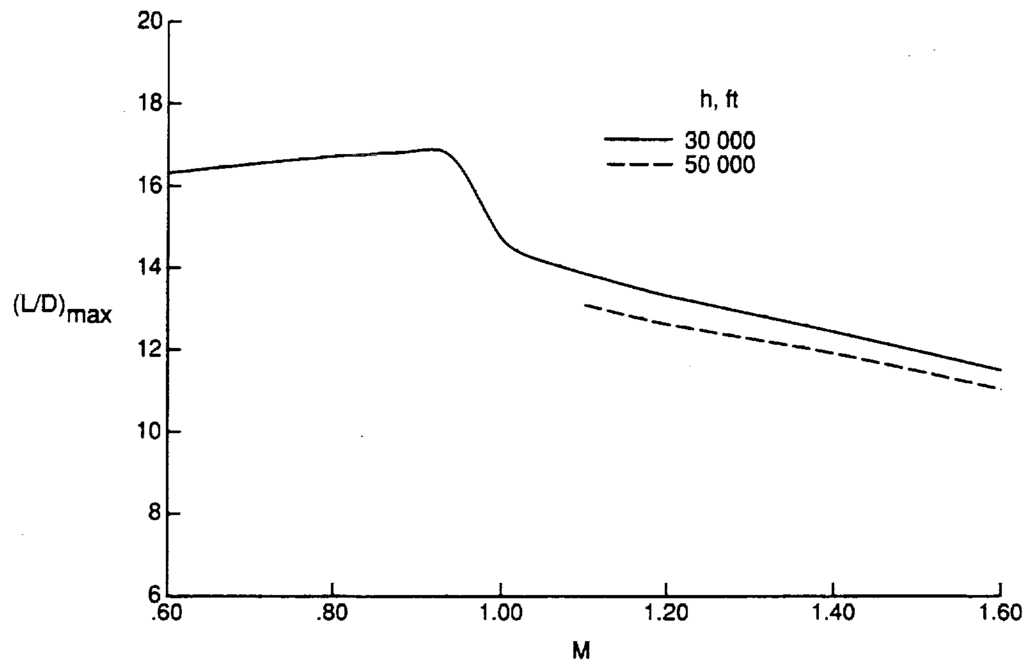


Figure 11. Maximum lift-to-drag ratios.

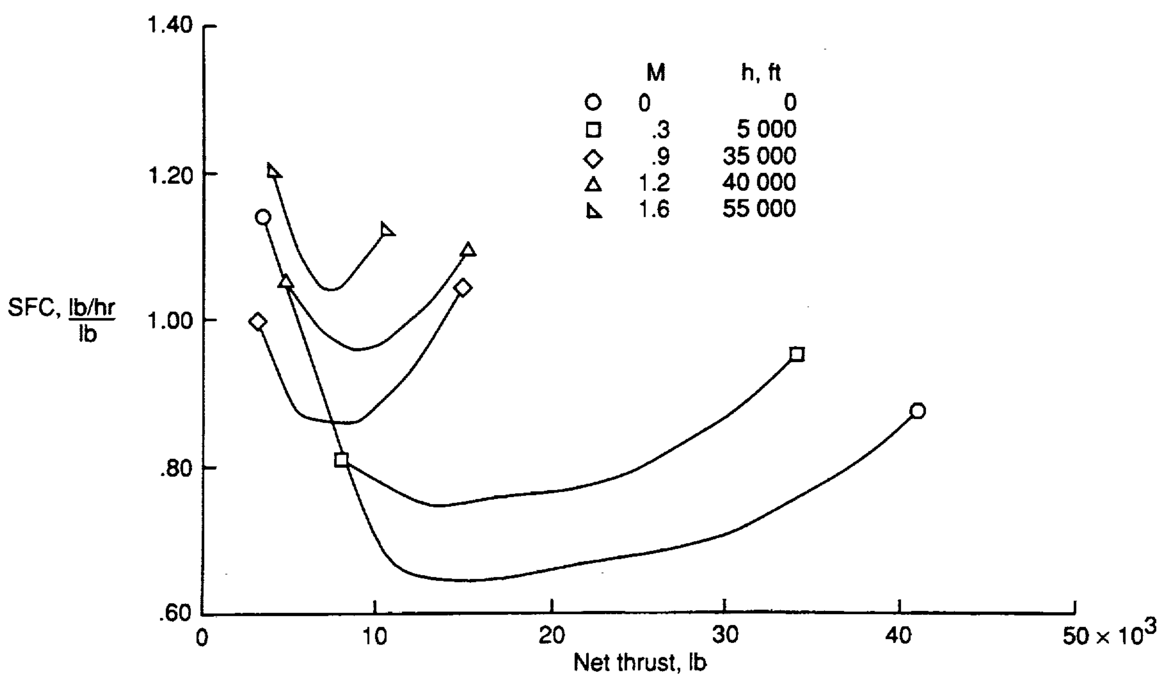


Figure 12. Engine specific fuel consumption (SFC) as a function of thrust.

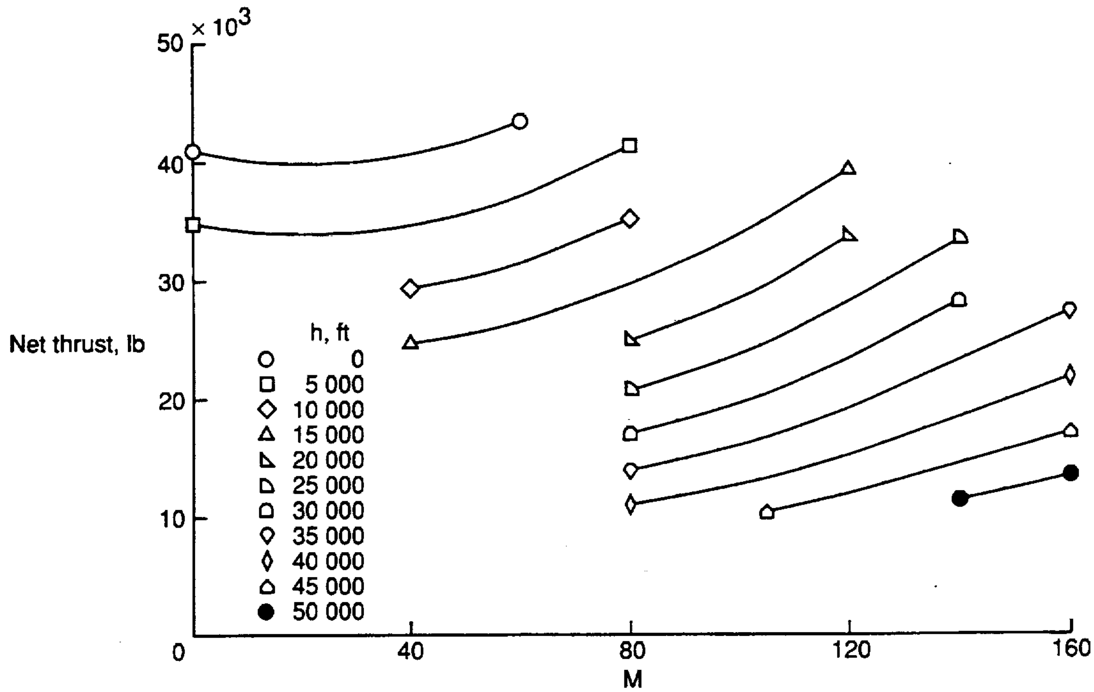


Figure 13. Engine thrust as a function of Mach number.

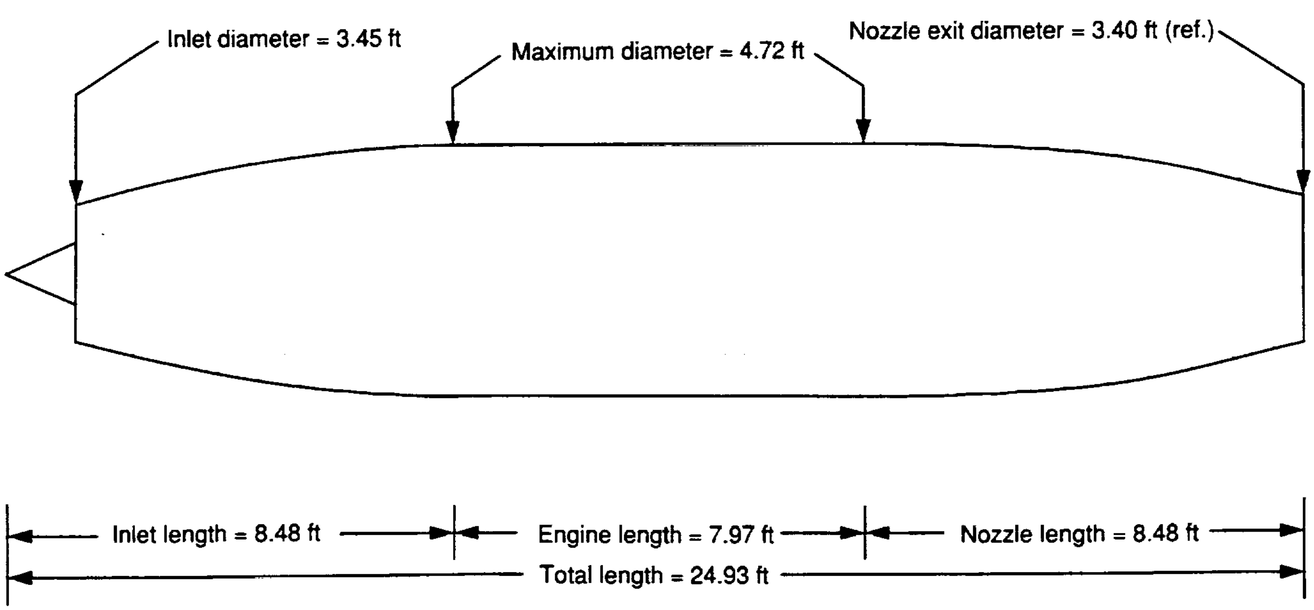


Figure 14. Nacelle and turbine bypass engine geometry scaled for 41 000 lb installed net thrust (takeoff).

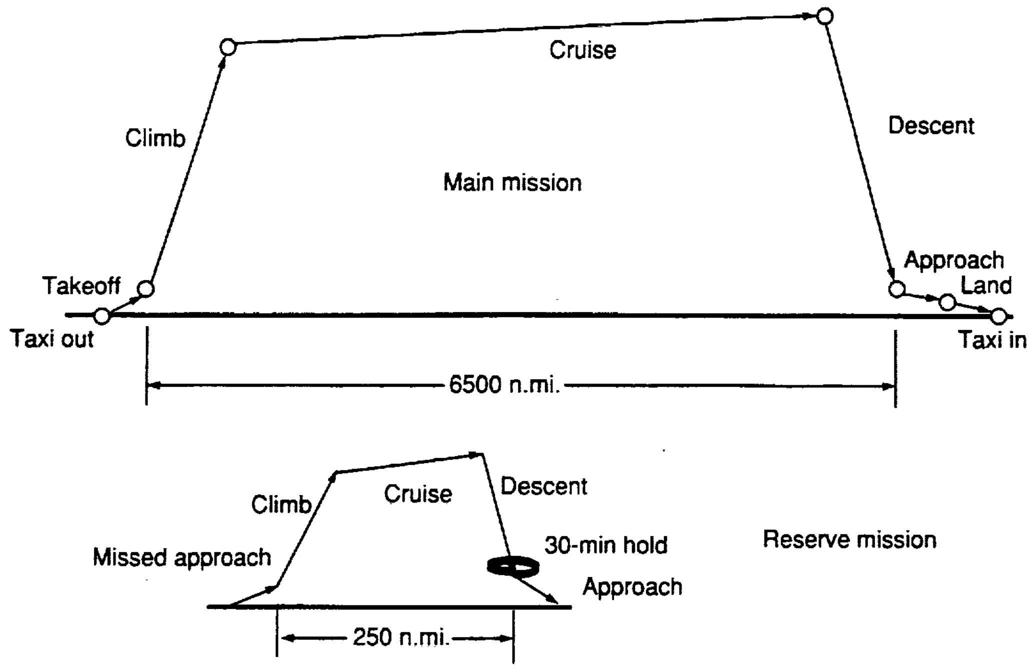


Figure 15. Profile of design and reserve missions.

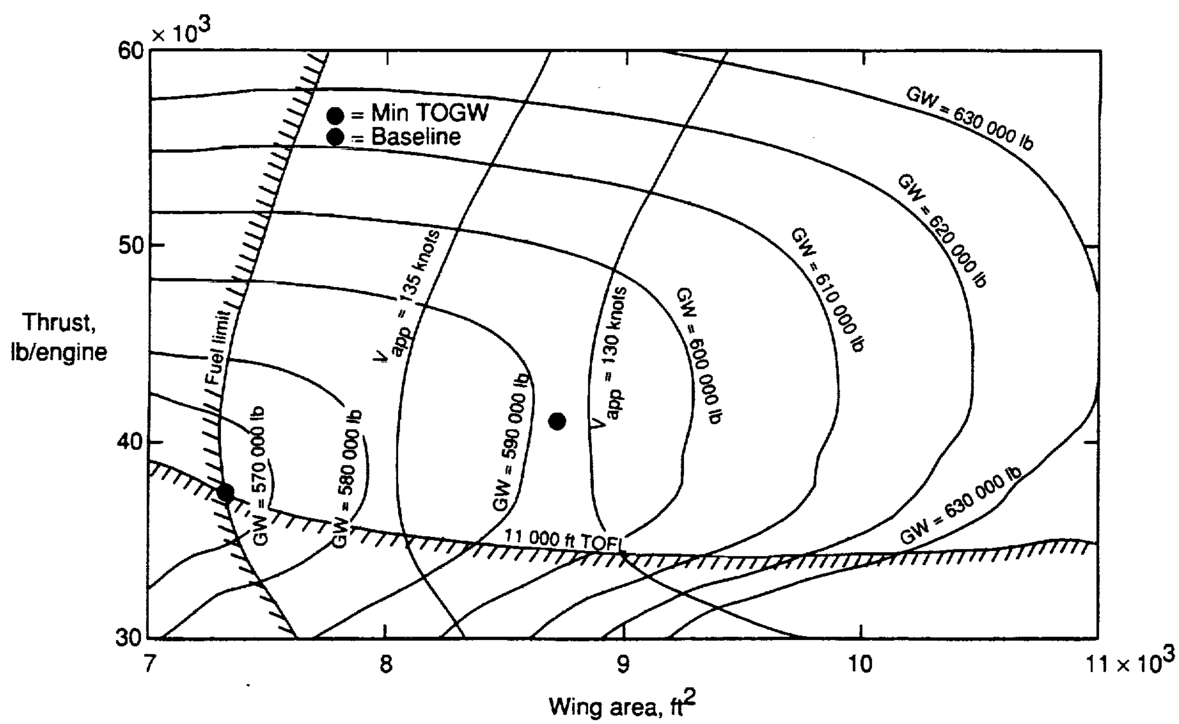


Figure 16. Sizing diagram for Mach 1.6 configuration.

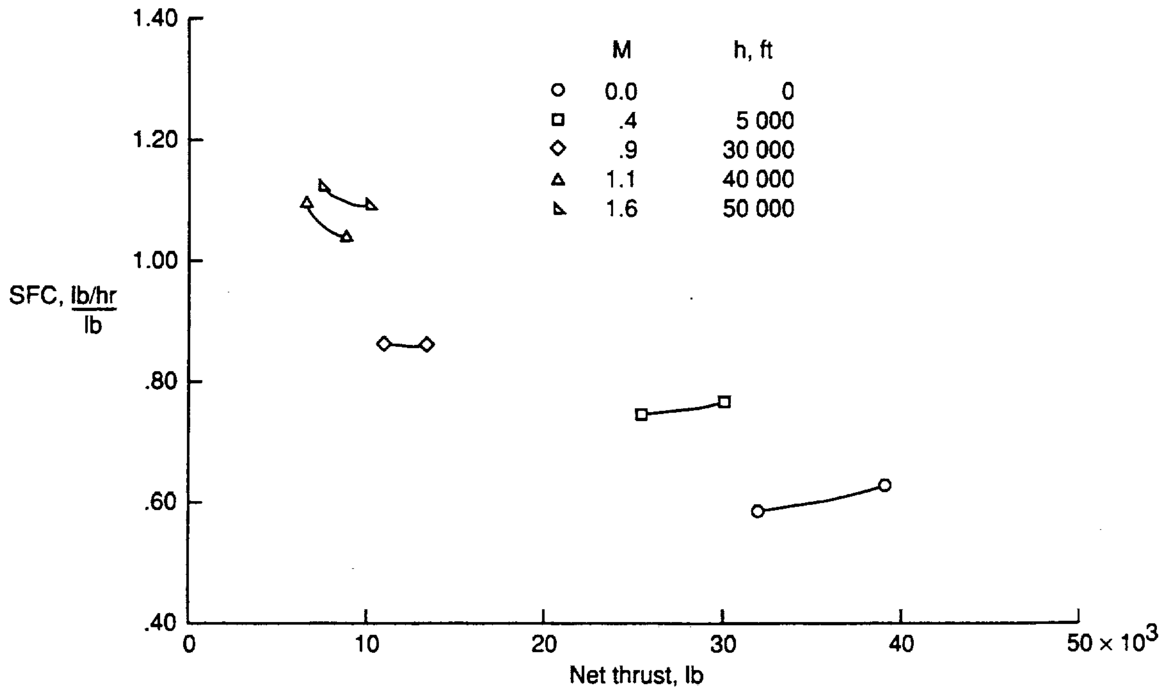


Figure 17. Alternate engine SFC as function of thrust.

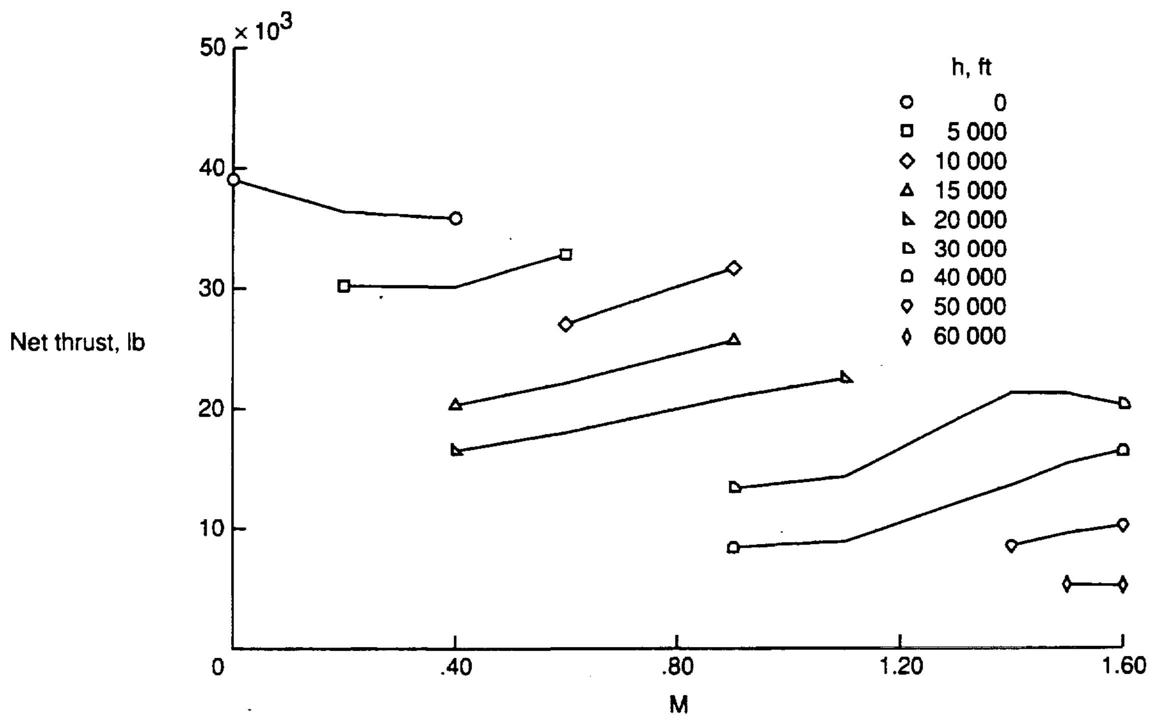


Figure 18. Alternate engine thrust as function of Mach number.

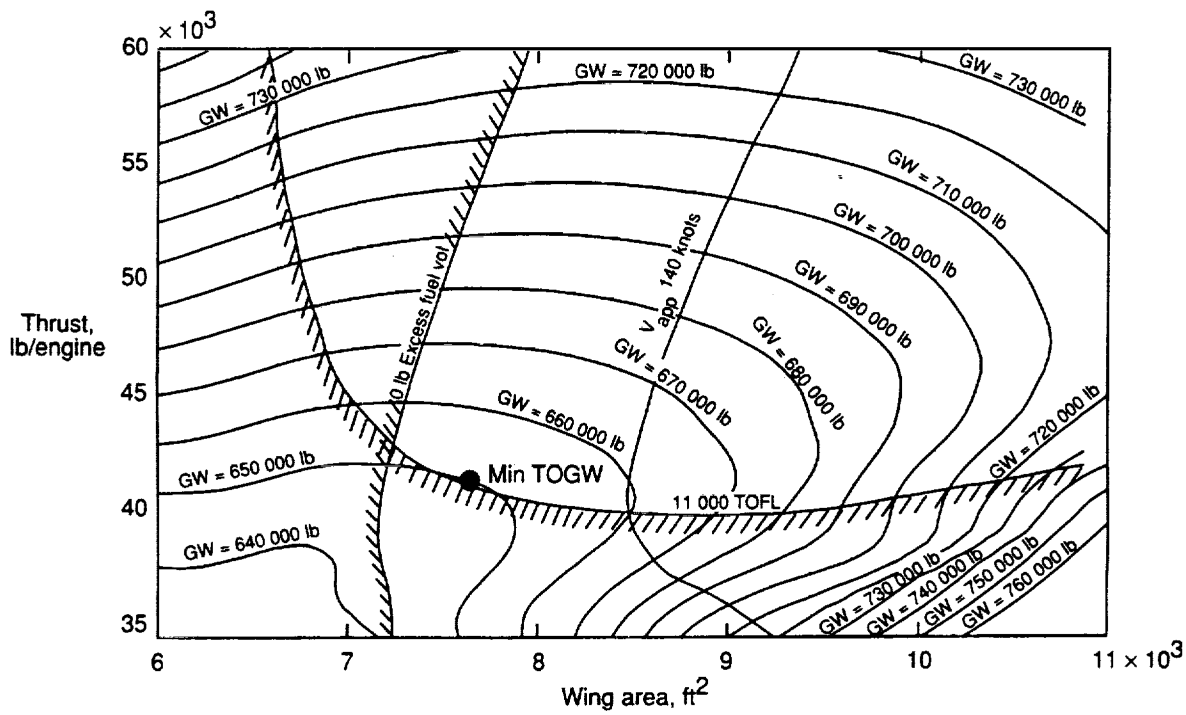


Figure 19. Sizing diagram for minimum TOGW configuration with alternate engines.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1999	Technical Publication

4. TITLE AND SUBTITLE
Concept Development of a Mach 1.6 High-Speed Civil Transport

5. FUNDING NUMBERS
WU 537-03-22-02

6. AUTHOR(S)
Elwood W. Shields, James W. Fenbert, Lori P. Ozoroski, and Karl A. Geiselhart

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17242

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TP-1999-209697

11. SUPPLEMENTARY NOTES
Shields, Ozoroski, and Geiselhart: Lockheed Engineering & Sciences Company, Hampton, VA; Fenbert: Langley Research Center, Hampton, VA.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category 05 Distribution: Nonstandard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
A high-speed civil transport configuration with a Mach number of 1.6 was developed as part of the NASA High-Speed Research Program to serve as a baseline for assessing advanced technologies required for an aircraft with a service entry date of 2005. This configuration offered more favorable solutions to environmental concerns than configurations with higher Mach numbers. The Mach 1.6 configuration was designed for a 6500 n.mi. mission with a 250-passenger payload. The baseline configuration has a wing area of 8732 ft^2, a takeoff gross weight of 591 570 lb, and four 41 000-lb advanced turbine bypass engines defined by NASA. These engines have axisymmetric mixer-ejector nozzles that are assumed to yield 20 dB of noise suppression during takeoff, which is assumed to satisfy the FAR Stage III noise requirements. Any substantial reduction in this assumed level of suppression would require oversizing the engines to meet community noise regulations and would severly impact the gross weight of the aircraft at takeoff. These engines yield a ratio of takeoff thrust to weight of 0.277 and a takeoff wing loading of 7.8 lb/ft that results in a rotation speed of 169 knots. The approach velocity of the sized configuration at the end of the mission is 131 knots. The baseline configuration was resized with an engine having a projected life of 9000 hr for hot rotating parts and 18 000 hr for the rest of the engine, as required for commercial use on an aircraft with a service entry date of 2005. Results show an increase in vehicle takeoff gross weight of approximately 58 700 lb. This report presents the details of the configuration development, mass properties, aerodynamic design, propulsion system and integration, mission performance, and sizing.

14. SUBJECT TERMS
Supersonic cruise; High-speed civil transport; Aircraft design; Transport aircraft

15. NUMBER OF PAGES
25

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102